THE **HIFI** HETERODYNE INSTRUMENT FOR **FIRST**: 
CAPABILITIES AND PERFORMANCE

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**ABSTRACT**

The Heterodyne Instrument for **FIRST (HIFI)** will cover at least the frequency range 492 GHz to 1113 GHz and will provide sensitive observations with resolving powers ranging from less than $5 \times 10^5$ to $1.2 \times 10^7$. The instrument is optimised for the measurement of weak, broad spectral lines of distant galaxies and for performing fast line surveys of galactic objects. This paper describes the performance, observing modes, and calibration modes of the planned instrument. Companion papers in these *Proceedings* describe the instrument optics, mixers and spectrometer systems.

1. **INTRODUCTION**

By virtue of its position in space, **FIRST** will observe for the first time the sub-millimetre wavelength transitions of many important chemical species which are presently obscured from ground-based or airborne observations by strong absorption in the Earth’s atmosphere. The heterodyne instrument on **FIRST** is intended to provide the capability of very high resolution spectroscopy from 610 $\mu$m down to about 250 $\mu$m. Two other instruments, the BOL and PHOC described elsewhere in these *Proceedings* [1, 2], will provide medium resolution spectroscopy and photometry over the wavelength interval 85 - 600 $\mu$m for this mission. The **FIRST** mission and satellite are described by Pilbratt [3] and Steinz [4] in these *Proceedings*.

A recent review of the scientific drivers for high-resolution spectroscopy at submillimetre wavelengths, with the emphasis on the stellar-interstellar life cycle, has been given by van Dishoeck & Helmich [5] (see also these *Proceedings*). They highlight the importance of complete spectral line surveys together with observations of transitions of the species H$_2$O, O$_2$, and HD which are difficult or impossible to observe from the ground or aircraft. In conclusion, they recommend continuous frequency coverage from the O$_2$ line at 487 GHz to the cluster of ortho-water transitions near 1700 GHz. Each of these sub-bands will occupy a different position in the focal plane and thus will not observe the same point on the sky. However, spacecraft resources permitting, it will be possible to operate two sub-bands simultaneously which may be used to advantage to map larger regions at two different frequencies.

Continuous frequency coverage will enable the detection of specific line emission from galaxies with arbitrary redshift. It will also provide complete and uniform line surveys across the sub-millimetre wavelength region allowing the comparison of different transitions of the same species to derive the physical conditions in the emitting region. Full frequency coverage will also allow intercomparison of **FIRST** observations with other ground and airborne observations in atmospheric windows.

The receiver will be optimised for the detection of broad weak line emission, for example from distant galaxies, and for high-speed line surveys of the ISM. To this end the instrument will be equipped with dual-polarisation receivers to maximise sensitivity, while the spectrometer bandwidth will be 4 GHz or more to...
increase the speed of line surveys. This will be wide enough to accommodate emission lines of up to 1000 km/s width over most of the frequency range of the instrument.

2.1 Architecture

Figure 1 is a block diagram of the HIFI instrument showing schematically the interconnection between the various systems and their placement in the satellite. The instrument consists of 6 units and these are described below.

**Focal Plane Unit**

The FPU sits inside the FIRST cryostat and shares the focal plane with the other two instruments. The area of the focal plane available to the HIFI instrument is 80x140 mm corresponding to about 11’x19’ on the sky. Relay optics within the FPU divides the beam from the telescope among the 5 dual polarisation mixer units covering each sub-band. A scanning mechanism within the relay optics will provide focal plane chopping and can be used to direct the receiver beam at a black body calibration source determination of the temperature scale.

Each mixer unit contains a pair of mixers accepting both signal polarisations for maximum sensitivity. The mixers themselves will be thermally strapped to the liquid helium tank and operate at a physical temperature of about 2 K whereas the rest of the FPU will be at about 10 K. The optics for injecting the local oscillator signal will be located within each mixer unit together with the IF preamplifiers. SIS mixers will be used up to 1250 GHz with hot-electron bolometer mixers for the high frequency channel.

The mixers will operate in double sideband (DSB) mode without image frequency filtering. This complicates the extraction of a calibrated SSB spectrum from the measurements but simplifies the instrument optics and reduces losses. Since there is no atmosphere, there is no penalty associated with emission in the image sideband. On the contrary, there is a speed advantage of a factor of 2 when performing a frequency survey.

**IF System**

The IF System amplifies the weak IF signals from the active mixers and distributes them among the spectrometers. Ten parallel IF channels will be required, one for each of the mixers in the FPU, and each will comprise a cascade of 3 amplifiers: one located within the FPU operating at 10 K, one on the outside of the cryostat at 100 K and one in the ambient temperature service module. This gain distribution is required to give maximum sensitivity within the constraints of the cryostat cooling limitations and the required cable lengths. Up to 4 IF channels may operate simultaneously allowing dual-frequency, dual-polarisation observations. The IF centre frequency depends on the mixer technology and the LO injection method used but is expected to be about 10 GHz for the SIS mixers. The instantaneous IF bandwidth will be greater than 4 GHz.

**Spectrometer System**

The spectrometer system performs the spectral analysis of the IF signals from the mixers. Two resolution bandwidth combinations are required: A wide band spectrometer will be implemented with a suite of acousto optic spectrometers (AOS) giving a frequency resolution of about 1 MHz and a total bandwidth of greater than 8 GHz. A high resolution mode will be implemented either with chirp transform spectrometers (CTS) or digital autocorrelation spectrometers (DACS) types giving a frequency resolution of less than 100 kHz and a total bandwidth of greater than 400 MHz. The system will be flexible allowing the available spectrometer bandwidth to be allocated among 2 to 4 active IF channels.

The spectrometer system will be located in the service module of the spacecraft. It will contain a microcontroller to configure the spectrometers and perform data pre-processing. The spectrometer system will receive commands and synchronisation signals from the main instrument controller and will return spectral data. The satellite will restrict the maximum science telemetry rate to 40 kbps which corresponds to about 2500 spectral channels per second without data compression.
**Local Oscillator Unit**

The LOU uses a combination of Gunn oscillators and cascaded varactor frequency multipliers to generate the high frequency local oscillator signals required to pump the mixers. Since the tuning range of currently available sub-mm LO sources is limited, a pair of sources will be required to cover the tuning range of each mixer sub-band. The LOU is located on the outside wall of the cryostat and will operate at a temperature of about 100 K. The LO signals are injected into the FPU through a window in the cryostat vacuum vessel.

**Local Oscillator Control Unit**

The LOCU contains the phase-lock electronics to control the frequency of the local oscillators. It will also provide the necessary bias and control voltages to operate the frequency multiplier chains and any associated mechanisms. The medium term frequency stability and line-width of the LO signals must be much less than 1 part in 10^7 to enable observations at velocity resolutions down to 50 m/s. However, the long term frequency stability is not so critical since this can be monitored and corrections applied off-line.

The LOCU will be located in the ambient temperature service module of the satellite. It is planned that the LOCU will contain its own microcontroller to take care of tuning and monitoring of the LO receiving its commands from the instrument controller.

**Instrument Control Unit**

The ICU provides the overall control of the instrument. It will receive commands through the satellite data bus, interpret them and pass on instructions to the LOCU and spectrometer systems. It will also provide control functions for the FPU by supplying the bias for the mixers and IF preamplifiers and driving the chopper and calibration unit. Another important function of the ICU will be the synchronisation of the observing process within the instrument and with the satellite attitude control system. In addition the ICU will distribute power to the other subsystems of the HIFI instrument.

The ICU will combine data from the spectrometers with housekeeping data before transmission to the satellite's on-board data handling system. The HIFI, and ICU in particular, must be designed to operate fully autonomously since FIRST will operate for up to 21 hours per day without contact with the ground. In this respect it is important that the instrument can detect faults and take corrective action automatically.

### 3. OPERATION

#### 3.1 Observing Modes

Three major observing modes are foreseen

- deep, point-source integrations,
- line surveys, and
- on-the-fly mapping.

For observations of a single point the technique of dual beamswitching will be used with the instrument focal plane chopper providing beamswitching with a throw of 3 arcmin. at up to 1 Hz. By repointing the satellite the source will be placed alternately in the two beams to cancel instrument baseline offsets, important for the detection of broad, weak lines.

For performing line surveys the local oscillator frequency will be stepped across the desired frequency range while making short integrations. The step size will be less than the IF bandwidth to give smooth continuous frequency coverage. By tracking spectral features in both sidebands of the mixer it will be possible to deconvolve the DSB measurements to generate an unaliased spectrum using a variation of CLEAN [12, 13], or maximum entropy techniques [14]. See Schilke et al [15] for a discussion of the application of these techniques to FIRST observations.

For mapping sources larger than the beamswitch throw, the technique of mapping-on-the-fly will be used. In this mode the telescope will make a raster scan across the source while simultaneously chopping with the focal plane chopper. The source structure can then be recovered using algorithms such as those described by Emerson et al [16] and Richer [17].

#### 3.2 Internal Temperature Calibration

The radiometer's effective DSB system temperature and gain in counts per Kelvin will be measured by chopping between blank sky and an internal black-body source at a variable temperature of between 10 to 80 K. For the estimated system temperatures given below, and neglecting systematic effects, the temperature difference will be sufficient to allow a calibration accuracy of about 1% for a 1 s calibration measurement.

#### 3.3 Flux Calibration

Observations of calibration sources of known flux or brightness temperature will be used to determine the telescope beam and aperture efficiencies. Table 1 lists the estimated antenna temperatures for the planetary and asteroidal continuum flux calibrators commonly used in the sub-mm wavelength region [18, 19, 20, 21, 22]. Due to spacecraft constraints, the range of allowed sun elongation angles (angle between the telescope boresight and sun direction) will be limited to 90 ±15° and this will preclude the observation of Venus, the
4. PERFORMANCE

4.1 Instrument Sensitivity

Zmuidzinas [23] and van de Stadt et al [24] have given recent reviews of the sensitivity of receivers in the sub-mm wavelength region. Current SIS mixers provide DSB receiver temperatures of 80 K at 500 GHz rising rapidly between 700 and 850 GHz to about 750 K at 1 THz. Recent results with HEB mixers include DSB receiver noise temperatures of 1900 K at 1.3 THz and 19% at 1.8 THz. However, we take the main beam and aperture efficiencies to be 90% and 60% independent of frequency.

For spectral line observations the relevant measure of system sensitivity is the single sideband noise temperature. Assuming a mixer sideband ratio of unity, as expected for a broad-band, fixed-tuned mixer, the SSB noise temperature is double that of the DSB value.

Table 1 lists the expected effective system noise temperatures and 5σ flux detection limits of HIFI at 3 frequencies (see text for details).

Table 2 lists the expected effective system noise temperatures at 500 GHz, 1 THz and 1.8 THz taking into account the above factors. Also listed are the 5σ flux detection limits for a spectral resolving power of \( R=10^5 \) and an integration time of 1 hour. Note that we ignore the \( \sqrt{2} \) improvement in sensitivity to be obtained when observing an unpolarised source by co-adding the measurements from both polarisations.

4.2 Observing Speed

Taking the instrument sensitivity outlined above, we can calculate the expected observing performance for three illustrative cases: a deep, point-source integration, a line survey, and mapping. As before we have not taken into account the possibility of co-adding polarisation channels to obtain higher sensitivity nor do we make any allowance for calibration and other overheads.

Deep Integration

For this case we will take a spectral resolution of \( R=10^4 \) (30 km/s velocity resolution). A 1 hour integration time gives the 5σ flux detection limits listed in Table 2.

Line Survey

We consider a spectral line survey to a specific noise level with a fixed frequency resolution of 1 MHz and with a spectrometer bandwidth of 4 GHz. We assume single-frequency operation – i.e. only one sub-band is operational at any one time. The 1.8 THz channel is
ignored since the likely tuning range is highly uncertain at this time. Note that for line surveys the effective IF bandwidth is doubled since both sidebands are measured simultaneously.

12 hours of observing is required achieve a uniform 1σ noise floor of 30 mK for a survey over 492 - 800 GHz. A similar survey to 100 mK noise level over the frequency interval 800 - 1113 GHz will take 18 hours.

**Mapping Speed**

For this case we calculate the mapping speed to achieve a specific noise level per (Nyquist sampled) pixel with a resolving power of \( R = 10^5 \). The calculation assumes dual-beam mapping is used and neglects any tracking overheads. The mapping speed in \( \text{arcmin}^2 \text{hr}^{-1} \) to achieve a given noise level are listed in Table 3.

### Table 3 The mapping speed in \( \text{arcmin}^2 \) per hour to achieve the stated noise level in a fully sampled map.

<table>
<thead>
<tr>
<th>Noise Level, ( \sigma T' / K )</th>
<th>500 GHz</th>
<th>1 THz</th>
<th>1.8 THz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mapping Speed ( \text{arcmin}^2 \text{hr}^{-1} )</td>
<td>170</td>
<td>9</td>
<td>5</td>
</tr>
</tbody>
</table>

4.3 Comparison with SOFIA

To illustrate the benefit of observing above the atmosphere we have compared the sensitivity of HIFI with an identical receiver operating on the planned SOFIA airborne observatory [26]. We have computed the flux detection limits for SOFIA taking the planned telescope characteristics from Becklin [26] together with modelled atmospheric transmission data supplied by M. Haas (private communication). The model atmosphere used is one for good observing conditions, namely a flight altitude of 41000 ft, a telescope elevation of 40°, and a zenith water vapour column of 5 µm. The results for spectral resolving powers of \( R = 10^3 \) and \( R = 10^5 \) are plotted in Figure 2 and show the effect of the forest of telluric absorption lines.

5. CONCLUSIONS

We have outlined the heterodyne instrument which is proposed for FIRST and estimated its likely performance. According to the current mission schedule, the instrument will be launched at the end of 2005 and will provide the first high resolution view of the sub-mm universe unaffected by absorption in the Earth's atmosphere.

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Figure 2 A comparison of the 5σ spectral flux density detection limits of FIRST and SOFIA for resolving powers of A) \( R=10^3 \), and B) \( R=10^5 \) (see text for details).
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7. REFERENCES


20. Hildebrand et al 1985, Icarus, 64, 64.


